

# Suzaku broad-band spectroscopy of RX J1347.5–1145: constraints on the extremely hot gas and non-thermal emission

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## ABSTRACT

**Context.** We present the results from the analysis of long Suzaku observations (149 ks and 122 ks for XIS and HXD, respectively) of the most X-ray luminous galaxy cluster, RX J1347.5–1145, at  $z = 0.451$ .

**Aims.** In order to understand the gas physics of a violent cluster merger, we study physical properties of the hot ( $\sim 20$  keV) gas clump in the south-east (SE) region discovered previously by the Sunyaev–Zel'dovich (SZ) effect observations. Using the hard X-ray data, a signature of non-thermal emission is also explored.

**Methods.** We perform single as well as multi temperature fits to the Suzaku XIS spectra. Then the Suzaku XIS and HXD, and the Chandra ACIS-I data are fit jointly to examine the properties of the hot gas component in the SE region. Finally, we look for non-thermal emission in the Suzaku HXD data.

**Results.** The single-temperature model fails to reproduce the 0.5–10 keV continuum emission and Fe-K lines measured by XIS simultaneously. The two-temperature model with a very hot component improves the fit, although the XIS data can only give a lower bound on the temperature of the hot component. We detect the hard X-ray emission in the Suzaku HXD data above the background in the 12–40 keV band at the  $9\sigma$  level; however, the significance becomes marginal when the systematic error in the background estimation is included. With the joint analysis of the Suzaku and Chandra data, we determine the temperature of the hot gas in the SE region to be  $25.3_{-4.5}^{+6.1}$  (statistical; 90% CL)  $_{-9.5}^{+6.9}$  (systematic; 90% CL) keV, which is in an excellent agreement with the previous joint analysis of the SZ effect in radio and the Chandra X-ray data. This is the first time that the X-ray analysis alone gives a good measurement of the temperature of the hot component in the SE region, which is made possible by Suzaku's unprecedented sensitivity over the wide X-ray band. These results strongly indicate that RX J1347.5–1145 has undergone a recent, violent merger. The spectral analysis shows that the SE component is consistent with being thermal. We find the  $3\sigma$  upper limit on the non-thermal flux,  $F < 8 \times 10^{-12}$  erg s $^{-1}$  cm $^{-2}$  in the 12–60 keV band, which provides a limit on the inverse Compton scattering of relativistic electrons off the CMB photons. Combining this limit with a recent discovery of the radio mini halo in this cluster at 1.4 GHz, which measures the synchrotron radiation, we find a lower limit on the strength of the intracluster magnetic field  $B > 0.007$   $\mu$ G.

**Key words.** galaxies: clusters: individual: RX J1347.5–1145 – galaxies: intergalactic medium – X-rays: galaxies: clusters – cosmology: observations

## 1. Introduction

RX J1347.5–1145 is one of the most extensively studied distant clusters of galaxies, located at  $z = 0.451$ , which is also known as the most X-ray luminous cluster of galaxies on the sky. The bolometric luminosity of RX J1347.5–1145 is  $L_{\text{X,bol}} \sim 2 \times 10^{46}$  erg s $^{-1}$  (Schindler et al. 1997).

The previous multi-wavelength observations have shown that RX J1347.5–1145 has an unusually violent merger activity, which makes this cluster an ideal target for probing the intracluster

gas physics and non-thermal phenomena associated with the cluster merger at high redshifts.

The global temperature of the intracluster medium (ICM) of RX J1347.5–1145 is as high as 9–14 keV, as indicated from observations with several X-ray satellites (Schindler et al. 1997; Ettori et al. 2001; Allen et al. 2002; Gitti et al. 2007b). This cluster has been classified as a “cooling-flow” cluster because of its centrally peaked X-ray surface brightness profile as well as of its high mass accretion rate estimated at the center (Schindler et al. 1997; Allen et al. 2002).

The most striking feature of RX J1347.5–1145 is the presence of an extremely hot,  $\sim 20$  keV, gas clump in the south-

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east (SE) region. This component was discovered by radio observations of the Sunyaev-Zel'dovich (SZ) effect towards RX J1347.5–1145 at 150 GHz as the prominent substructure of the SZ effect in the SE region, about 10'' off of the center (Komatsu et al. 2001). Kitayama et al. (2004) have performed a detailed joint analysis of the SZ effect decrement data at 150 GHz (Komatsu et al. 2001), increment data at 350 GHz (Komatsu et al. 1999), and the *Chandra* ACIS-S3 X-ray data (Allen et al. 2002), and determined the temperature of the hot gas clump to be in excess of 20 keV, which is much higher than the average temperature of ambient gas.

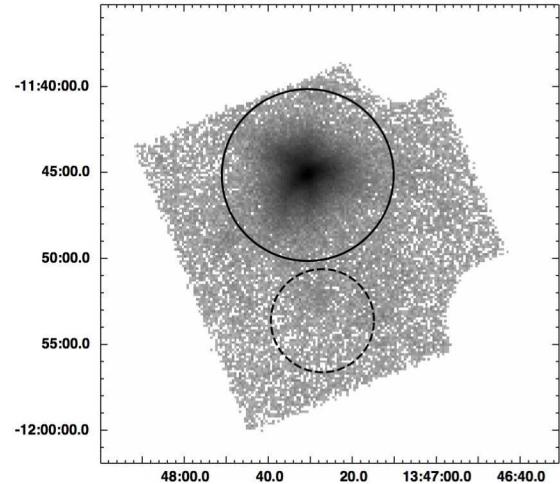
The coexistence of the cool and hot ICM in the central region indicates a complex dynamical evolution of the system, such as a recent merger. In the optical band, the cluster center is dominated by two cD galaxies. The dark matter distribution has also been studied through the gravitational lensing effect (e.g., Fischer & Tyson 1997; Sahu et al. 1998; Cohen & Kneib 2002; Allen et al. 2002; Bradač et al. 2008; Miranda et al. 2008; Halkola et al. 2008). An elongated, nearly bimodal distribution was found (Bradač et al. 2008), which also points to the cluster merger. Another line of evidence for the merger comes from a recent discovery of the radio mini halo at the cluster center (Gitti et al. 2007a), which suggests the presence of relativistic particles powered by the merger as well as by the cooling flow.

The X-ray data from the *ROSAT* satellite (Schindler et al. 1997) failed to identify the hot component in the SE region, as its X-ray sensitivity did not extend to such a high temperature. In fact, RX J1347.5–1145 had been considered as a *relaxed*, non-merging cluster until the SZ effect revealed the evidence for a violent merger. This example shows the importance of having sensitivity to high temperatures well in excess of 10 keV.

Such a high temperature component seems common in merging clusters. Another, perhaps most famous, example is the Bullet cluster (1E0657-56), in which the hot gas substructure has also been found (Markevitch et al. 2002). The analysis of the temperature structure in merging clusters is a powerful tool for understanding the gas physics in extreme conditions. While the X-ray spectroscopy has been used widely for this sort of study, it is not very easy to precisely measure the temperature of very hot gas, as the majority of X-ray imaging spectroscopic observations are limited to the energy band below 10 keV, and thus they cannot measure a spectral cut-off at  $kT$  characteristic of the thermal bremsstrahlung emission.

To overcome this difficulty, Kitayama et al. (2004) used the fact that the SZ effect is sensitive to arbitrary high temperature gas, and performed a joint analysis of the SZ effect and X-ray images. They have determined the temperature of the SE excess component in RX J1347.5–1145 to be  $28 \pm 7$  keV, while the *Chandra* X-ray spectroscopy, whose sensitivity degrades significantly beyond 7 keV, gave the lower limit of 22 keV. This is one of the hottest gas known to date. Based on the numerical simulations by Takizawa (1999), Kitayama et al. (2004) suggested that RX J1347.5–1145 has undergone a recent merger at the collision speed of  $4500 \text{ km s}^{-1}$ , which is very similar to what has been found more recently from the Bullet cluster (Milosavljević et al. 2007; Springel & Farrar 2007; Mastropietro & Burkert 2007; Nusser 2008). This result is indicative of RX J1347.5–1145 being essentially the Bullet cluster, except for the viewing angle.

The conclusion of Kitayama et al. (2004) relies on the SZ data from high-resolution mapping observations of the SZ effect (the highest resolution ever achieved to date; Komatsu et al. 1999, 2001). However, precision of such SZ observations is still limited due to technological reasons; thus, high-precision X-ray observations whose sensitivity goes well beyond 10 keV are re-



**Fig. 1.** *Suzaku* XIS-0 image of RX J1347.5–1145 in the 0.5–10 keV band. The spectral integration regions for the cluster and the background are indicated with the solid and dashed circles, respectively. The two corners of the CCD chip illuminated by  $^{55}\text{Fe}$  calibration sources are excluded from the image.

quired to obtain reliable estimates of physical properties such as the temperature and merging velocity.

The unprecedented sensitivity of the *Suzaku* satellite (Mitsuda et al. 2007) to hard X-ray emission well over 10 keV offers a great opportunity for studying violent merger events. In this paper we present an analysis of the temperature structure and non-thermal, high-energy component in the distant cluster RX J1347.5–1145 with the on-board instruments, the X-ray Imaging Spectrometer (XIS; Koyama et al. 2007), and the Hard X-ray Detector (HXD; Takahashi et al. 2007; Kokubun et al. 2007). These instruments provide high-sensitivity spectroscopic observations in a wide energy band up to several tens of keV. Combined with the *Chandra* data, we determine the temperature of the SE clump *only from the X-ray spectroscopy*, and discuss its physical properties. We also constrain, for the first time, the non-thermal hard X-ray emission and estimate the magnetic field strength in RX J1347.5–1145.

Throughout this paper we adopt a cosmological model with the matter density  $\Omega_M = 0.27$ , the cosmological constant  $\Omega_\Lambda = 0.73$ , and the Hubble constant  $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , which are consistent with the WMAP 5-year results (Dunkley et al. 2008; Komatsu et al. 2008). At the cluster redshift ( $z = 0.451$ ),  $1''$  corresponds to 5.74 kpc. Unless otherwise specified, quoted errors indicate the 90% confidence range.

## 2. Observation and data reduction

Long observations of RX J1347.5–1145 were carried out twice in the *Suzaku* AO-1 period. During the observations, XIS and HXD were operated in their normal modes. To prioritize the HXD effective area, the target was observed at the HXD nominal aim-point (i.e., 3'.5 off-axis relative to the XIS). The total exposure time after data filtering is 149 ks/122 ks for XIS/HXD. The summary of the observations is given in Table 1.

The XIS consists of four X-ray CCD cameras: three front-illuminated CCDs (XIS-0, -2, -3: 0.4–12 keV) and one back-illuminated CCD (XIS-1: 0.2–12 keV), and covers a field of view of  $18' \times 18'$ . The “Spaced Charge Injection” option was not applied. The energy resolution was  $\sim 160 \text{ eV}$  at 6 keV

**Table 1.** Log of *Suzaku* observations of RX J1347.5–1145.

Target	Sequence No.	Date	Coordinates <sup>a</sup>		Exposure [s] <sup>b</sup>	
			RA [deg]	Dec [deg]	XIS	PIN
RXJ1347.5-1145	801013010	2006-06-30	206.8560	-11.8093	69661	56698
RXJ1347.5-1145	801013020	2006-07-15	206.8558	-11.8095	79126	64922

<sup>a</sup> Pointing coordinates in J2000.<sup>b</sup> Net exposure time after data filtering.

(FWHM) at the time of the observations. As shown in Fig. 1, the X-ray emission from the cluster is clearly detected. The X-ray peak position (13:47:30.3, -11:45:00.9) is consistent with that obtained from the *Chandra* (13:47:30.6, -11:45:09.3) within the accuracy of the attitude determination of *Suzaku* (typically < 20"; Uchiyama et al. 2008).

The non-imaging HXD covers a wide bandpass of 10–600 keV with PIN diodes (10–60 keV) and GSO scintillator (40–600 keV). We shall use the PIN data in this paper. The narrow field of view of  $\sim 30' \times 30'$  (FWHM) and the low background level of the PIN spectral data enable us to study the hard X-ray emission from the cluster up to several tens of keV, ideal for studying a violent merger event. The bias voltage from one of four high-voltage units was reduced from the nominal value of 500 V to 400 V. As a result the total effective area of the HXD/PIN decreased by about a few % above 20 keV. This effect is incorporated in the detector response functions.

We use the cleaned event files created by the pipeline processing version 2.0, and perform the data analysis using HEASOFT version 6.3.1. The XIS data was filtered according to the following criteria: the Earth elevation angle  $> 10^\circ$ , the day-Earth elevation angle  $> 20^\circ$ , and the satellite outside the South Atlantic Anomaly (SAA). The HXD data was filtered according to the following criteria: the Earth elevation angle  $> 5^\circ$ , the geomagnetic cut-off rigidity (COR)  $> 6$  GV, and the satellite outside the SAA.

The XIS spectra were extracted from a circular region within a radius of 5' that is centered at the X-ray peak position (see Fig. 1). The background spectra were accumulated from the circular region within a 3' radius which is almost free from the cluster emission. Since the background contributes 10–15% to the total spectra, the systematic error due to the background uncertainty is small. To confirm this, we have checked the position dependence of the background spectra by analyzing the blank-sky data obtained during the  $\sim 90$  ks North Ecliptic Pole observation on 2006-02-10, and found that it is smaller than 7% for all of the four sensors of XIS. Therefore, the background does not affect our spectral analysis within the statistical errors.

The energy response files were generated by using the FTOOLS task, `xissrmfgen`. In order to take into account the vignetting effect of the X-ray telescopes (XRT; Serlemitsos et al. 2007) and a decrease of the low-energy efficiency due to the contaminating material on the optical blocking filter of the XIS, the auxiliary response files (arf) were calculated by using `xissimarfgen` (Ishisaki et al. 2007). Here, we assume that the X-ray surface brightness distribution of the cluster is represented by the double  $\beta$ -model: our reanalysis of the *Chandra* ACIS-I image yields the two core radii given by  $r_{c1} = 24$  kpc and  $r_{c2} = 94$  kpc, the same slope parameter,  $\beta = 0.63$ , for both components, and a surface brightness ratio of  $S_1/S_2 = 8.1$  at the center (see Fig. 9b). Since the spatial distribution of RX J1347.5–1145 is compact compared to the typical size of the *Suzaku*'s Point Spread Function (PSF), its detailed feature does not sig-

nificantly affect our spectral analysis: if we compare the above arf files with those produced assuming a point-like source or an exposure-corrected *Chandra* image as an input source distribution, these three kinds of arfs agree within 3% and give consistent spectral parameters within the present calibration uncertainty of the *Suzaku* telescope (see also Appendix A).

The hard X-ray spectra were accumulated from all units of the PIN diodes. The PIN detector background was subtracted by using the Non-X-ray Background (NXB) files<sup>1</sup> provided by the HXD instrument team. Since precise modeling of the background is crucial for measuring the hard X-ray flux, we describe the method of background subtraction in §4. In the spectral fitting, we use the PIN response function<sup>2</sup> that is appropriate for the epoch of observations.

### 3. XIS analysis: 0.5–10 keV

In order to examine the global temperature structure of RX J1347.5–1145, we fit the APEC thermal emission model to the observed XIS spectra in the 0.5–10 keV band.

The angular size of the X-ray emission is fairly compact and nearly 90% of the total emission comes from the central  $r < 2'$  region, which is comparable to the spatial resolution of the *Suzaku* XRT (Half Power Diameter  $\sim 2'$ ; Serlemitsos et al. 2007). We use the extraction radius of 5'; thus, more than 97% of the photons from RX J1347.5–1145 are collected.

#### 3.1. Fitting with the single-temperature model

The XIS spectra with high photon statistics allow us to measure the global temperature in two different ways: (1) the APEC model fit to the 0.5–10 keV spectra, and (2) the use of the intensity ratio of two Fe emission lines, namely (He-like Fe  $K\alpha$ )/(H-like Fe  $K\alpha$ ), as an indicator of the "ionization" temperature. By comparing these two, we examine whether the emission can be modeled by the single-temperature gas, or the data require more complex temperature structure.

For the analysis (1) (APEC model), we fit the APEC model to the observed 0.5–10 keV XIS spectra, where the redshift and the Galactic hydrogen column density were fixed at  $z = 0.451$  and  $N_{\text{H}} = 4.85 \times 10^{20} \text{ cm}^{-2}$  (Dickey & Lockman 1990), respectively. The metal abundances table in Anders & Grevesse (1989) was assumed. The spectral bins in the 1.7–1.9 keV range were excluded due to the large calibration errors in the Si-edge structure. In order to take into account the uncertainty in the thickness of the contaminating material, the absorption column densities of oxygen and carbon ( $N_{\text{C}}$  and  $N_{\text{O}}$ ) were included in the spectral model with the ratio fixed at  $N_{\text{C}}/N_{\text{O}} = 6$ . In addition, there is a potential uncertainty in the absolute energy scale on the order

<sup>1</sup> [http://www.astro.isas.jaxa.jp/suzaku/analysis/hxd/pinnxb/pinnxb\\_ver2.0/](http://www.astro.isas.jaxa.jp/suzaku/analysis/hxd/pinnxb/pinnxb_ver2.0/)<sup>2</sup> ae\_hxd\_pinhxname2\_20070914.rsp

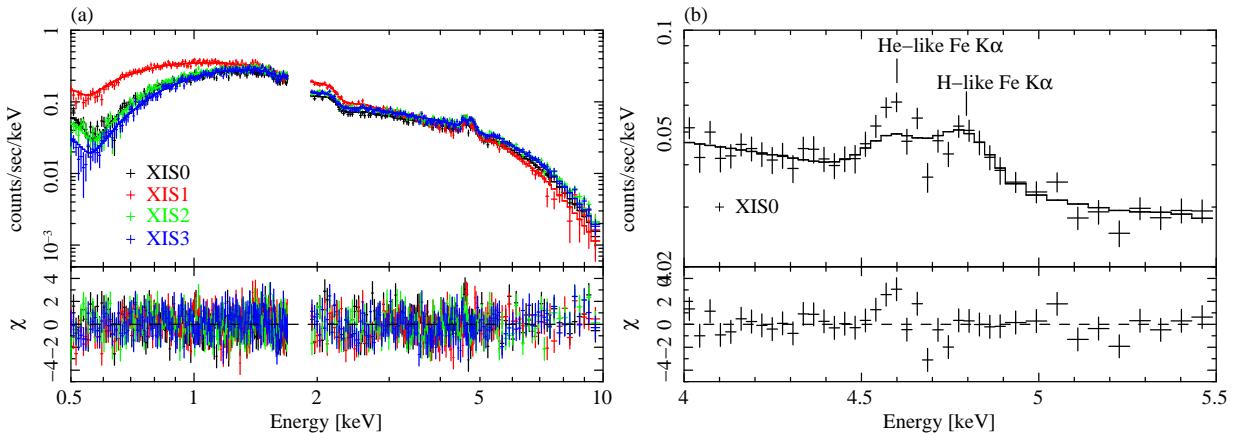
**Table 2.** Single-temperature APEC model parameters fit to the XIS spectra taken by four sensors (XIS-0, XIS-1, XIS-2, XIS-3), and the result from the simultaneous fit to all of the sensors (XIS-0, 1, 2, 3).

Sensor	$kT$ [keV]	$Z$ [solar]	$K^a$	$\chi^2/\text{dof}$
XIS-0	13.31(12.76 – 13.86)	0.35(0.28 – 0.40)	1.37(1.37–1.39)×10 <sup>–2</sup>	352.1/298
XIS-1	12.23(11.54 – 12.83)	0.36(0.30 – 0.41)	1.41(1.39–1.44)×10 <sup>–2</sup>	345.0/298
XIS-2	12.87(12.40 – 13.32)	0.34(0.29 – 0.38)	1.40(1.38–1.42)×10 <sup>–2</sup>	316.5/298
XIS-3	12.76(12.28 – 13.24)	0.30(0.25 – 0.35)	1.45(1.43–1.47)×10 <sup>–2</sup>	300.2/298
XIS-0,1,2,3	12.86(12.61 – 12.94)	0.33(0.31 – 0.36)	1.37(1.36–1.39)×10 <sup>–2</sup>	1320.4/1198

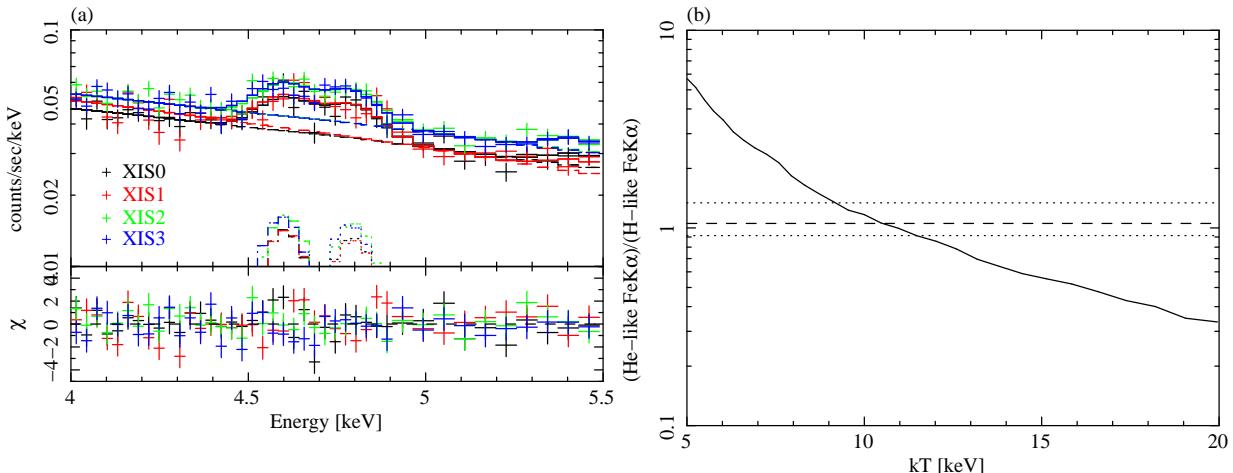
<sup>a</sup> The APEC normalization,  $K = \int n_e n_H dV / (4\pi D_A^2 (1+z)^2)$  [10<sup>14</sup> cm<sup>–5</sup>].

**Table 3.** The instrumental calibration parameters from the APEC model fit simultaneously to the XIS-0, 1, 2, and 3.

Sensor	Relative normalization	$N_c$ [10 <sup>18</sup> cm <sup>–2</sup> ]	Gain offset [eV]
XIS-0	1(Fix)	0.012(< 0.116)	–12.0 (–20.0–6.0)
XIS-1	1.035(1.023–1.047)	0.093(0.014–0.184)	–16.0 (–22.5–10.2)
XIS-2	1.019(1.007–1.030)	0.011(< 0.116)	–9.8 (–16.5–3.1)
XIS-3	1.049(1.038–1.060)	0.000(< 0.100)	–20.1 (–26.4–14.2)



**Fig. 2.** (a) Observed XIS spectra ( $r < 5'$ ). The spectra taken by four sensors, XIS-0 (black), 1 (red), 2 (green), and 3 (blue), are shown separately. The solid lines in the upper panel show the best-fitting single-temperature APEC thermal plasma model simultaneously fit to all of the sensors, convolved with the telescope and the detector response functions. In the bottom panel the residuals of the fit in units of the number of standard deviations are shown. (b) Blow-up of the XIS-0 spectrum in the 4–5.5 keV band. The single-temperature model fails to fit the He-like Fe K $\alpha$  line.



**Fig. 3.** (a) Observed XIS spectra in the 4–5.5 keV band. The spectra taken by four sensors, XIS-0 (black), 1 (red), 2 (green), and 3 (blue), are shown separately. The solid lines in the upper panels are the best-fitting continuum plus two Gaussian models. In the bottom panel the residuals of the fit in units of the number of standard deviations are shown. (b) Line ratio (He-like Fe K $\alpha$ )/(H-like Fe K $\alpha$ ) as a function of temperature, calculated from the APEC model. The horizontal dashed line and the dotted lines show the best-fitting line ratio and the 90% confidence interval, respectively.

of 10–20 eV, as indicated from the analysis of the  $^{55}\text{Fe}$  calibration source spectra; thus, the gain offset for each XIS sensor is included in the fitting model.

Since all of the four sensors yield consistent APEC parameters (see Table 2), we shall show the results from the simultaneous fit to all of the sensors (XIS-0, XIS-1, XIS-2, and XIS-3) hereafter. When performing the simultaneous fit, the normalizations of XIS-1, XIS-2, and XIS-3 relative to that of XIS-0 were also treated as free parameters. We find the temperature and the metal abundance of  $kT = 12.86^{+0.08}_{-0.25}$  keV and  $Z = 0.33^{+0.03}_{-0.02}$  solar, respectively. The unabsorbed flux and luminosity in the 0.5–10 keV band are  $F_{\text{X},0.5-10 \text{ keV}} = 1.3 \times 10^{-11}$  erg s $^{-1}$  cm $^{-2}$ , and  $L_{\text{X},0.5-10 \text{ keV}} = 8.7 \times 10^{45}$  erg s $^{-1}$ , respectively. The estimated bolometric X-ray luminosity is  $L_{\text{X,bol}} = 1.37 \times 10^{46}$  erg s $^{-1}$ . In Table 3 we list the the instrumental calibration parameters. In the following analysis we shall use the best-fitting values for the relative normalization factors, the carbon column densities, and the gain offsets.

Fig. 2 shows the observed XIS spectra. Fig. 2b is a blow-up of the region around the redshifted He-like Fe  $\text{K}\alpha$  and H-like Fe  $\text{K}\alpha$  lines at about 4.6 keV and 4.8 keV, respectively. We find clear detections of both lines. Also shown is the best-fitting single-temperature APEC thermal plasma model. The single-temperature model fails to fit the He-like line. The reduced  $\chi^2$  from the single-temperature fit is  $\chi^2 = 1320.4/1198$ ; thus, the single-temperature model is rejected at the 99.3% C.L.

We then attempt to fit the XIS spectra with the NEI (Non-equilibrium ionization collisional plasma) model. We found that the NEI model does not improve the fit to the He-like Fe  $\text{K}\alpha$  line and the quality of the fit in the whole energy range is similar to the 12.9 keV APEC model: the resulting  $\chi^2$  from the NEI model fit is 1340 for 1208 degrees of freedom. Moreover, the best-fit ionization timescale of  $> 10^{12}$  s cm $^{-3}$  is actually long enough for the system to reach the equilibrium state (Masai 1994), and thus the assumption that the system is in a non-equilibrium state cannot be justified. From these results we conclude that the single-temperature NEI model fails to describe the observed XIS spectra.

For the analysis (2) (line ratio), we model the observed XIS spectra in the 4–5.5 keV band by the sum of the following components: (i) the APEC model with the metal abundance reset to 0 for the continuum emission, (ii) two Gaussian functions for the two major Fe lines at 4.6 and 4.8 keV, and (iii) another Gaussian line at 5.4 keV for the blend of the He-like Ni- $\text{K}\alpha$  and He-like Fe- $\text{K}\beta$  lines. In Fig. 3a we show the results of the fit. This model gives an acceptable fit to the data with  $\chi^2/\text{dof} = 185/163$ , or the probability of finding higher  $\chi^2$  values than observed is 11.4%.

This model provides the line ratio, (He-like Fe  $\text{K}\alpha$ )/(H-like Fe  $\text{K}\alpha$ ), of 1.05(0.92 – 1.34). Fig. 3b shows the temperature dependence of the line ratio predicted by the APEC model, folded with the XRT+XIS response functions. From this we find  $kT = 10.4(9.1 - 11.4)$  keV, which is significantly different from that found in the analysis (1),  $kT = 12.86(12.61 - 12.94)$  keV, suggesting that the ICM cannot be explained by the single-temperature model. Therefore, the ICM is more likely to be in the form of multi-temperature plasma, which we shall explore in § 3.2.

Since the iron lines are emitted mostly from low-temperature gas (see §3.2), the line energies and widths are useful probes of (i) the gas bulk motion and (ii) the turbulence in the cluster core. For (i), the observed centroid energies of the iron lines are consistent with those expected from the 10 keV APEC model (6.69 and 6.97 keV in the rest frame) and the cluster redshift, to within the 90% statistical error of 10 eV. As shown in Table 3, there

is the gain offset of 15 eV when averaged over the four XIS sensors, we simply assign the 90% systematic error of 15 eV to the XIS energy scale. Then by adding the statistical and systematic errors in quadrature, the 90% upper limit on the line-of-sight bulk velocity relative to  $z = 0.451$  is estimated as  $\Delta V < 1200$  km s $^{-1}$ . (ii) We find no significant line broadening: the 90% upper limit on the Gaussian width of the He-like  $\text{K}\alpha$  line is  $\sigma_{\text{measured}} < 35$  eV. Since the measured Gaussian width is the sum of the thermal Doppler broadening,  $\sigma_0$  ( $\sigma_0 = 4$  eV for  $kT = 10$  keV), and the broadening due to a turbulent velocity,  $\sigma_{\text{turb}}$ , i.e.,  $\sigma_{\text{measured}}^2 = \sigma_0^2 + \sigma_{\text{turb}}^2$ , an upper limit on the turbulent velocity dispersion is obtained as  $\sigma_{\text{turb}} < 1500$  km s $^{-1}$ . Therefore we did not find from the analysis of the iron lines any significant bulk velocity and the turbulent velocity, which is consistent with the view that the low-temperature gas in the cluster core is relatively relaxed. The derived upper limits are also comparable to those obtained for the core of the Centaurus cluster (Ota et al. 2007). If the velocity structure on a small (< 2') spatial scale exists, the signals may be diluted due to the wide PSF of *Suzaku*. However, it is not easy to study the detailed spatial structure in RX J1347.5–1145 because the angular size is small.

### 3.2. Fitting with the two-temperature model

Given that the single-temperature model fails to describe the observed XIS spectra, we explore the two-temperature model consisting of two APEC models with different temperatures, as the simplest case of the multi-temperature plasma. The results of the fit to the two-temperature model are shown in Fig. 4 and Table 4, where the metal abundances of the two components are assumed to be equal.

From the fit to the 0.5–10 keV spectra, we find that the low-temperature component has the temperature of  $kT_{\text{low}} = 9.7^{+0.7}_{-1.1}$  keV<sup>3</sup>, whereas we only find a lower bound on the temperature of the high-temperature component as  $kT_{\text{high}} > 33$  keV. This two-temperature model yields an acceptable goodness-of-fit: the reduced  $\chi^2$  is  $\chi^2 = 1295.0/1207$ , or the probability of finding higher  $\chi^2$  values than observed is 3.9%. In comparison to the single-temperature APEC model, the fit has improved at more than the 99.99% confidence level according to the F-test ( $\Delta\chi^2 = 25$  for two additional parameters). Restricting the energy range to 4.0–5.5 keV does not change the parameters significantly (see the lower row of Table 4). The reduced  $\chi^2$  is  $\chi^2 = 185.2/159$ , or the probability of finding higher  $\chi^2$  values than observed is 7.6%.

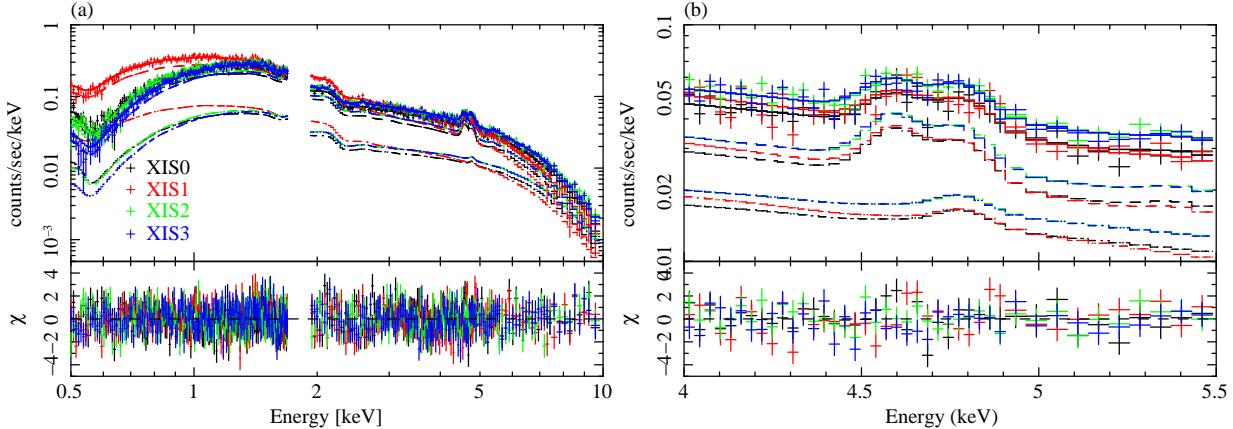
Since the observed Fe  $\text{K}\alpha$  lines should be totally dominated by the low-temperature gas (see Fig. 4b), one may compare  $kT_{\text{low}} = 9.7^{+0.7}_{-1.1}$  keV and the temperature derived from the line ratio,  $kT = 10.4(9.1 - 11.4)$  keV (see § 3.1), directly. These two estimates are in an excellent agreement, which gives a support for the two-temperature interpretation of the ICM of RX J1347.5–1145.

Although the XIS spectra give the lower bound on the temperature of the hotter component (see Table 4), they fail to give the upper bound. We find that this is due to the two-temperature model being too simple to be realistic. More detailed modeling on the hotter component, including a joint analysis with the *Suzaku* HXD data and the spatially-resolved *Chandra* data, will be given in § 5.

<sup>3</sup> The temperature of the low-temperature component is similar to the temperature determined from the spectra taken by the GIS detectors on board *ASCA* with the single-temperature model,  $kT_{\text{ASCA}} = 9.3^{+1.1}_{-1.0}$  keV (Schindler et al. 1997).

**Table 4.** Two-temperature APEC model parameters fit to the XIS spectra in the 0.5–10 keV and 4.0–5.0 keV bands.

Energy band	$i$	$kT_i$ [keV]	$Z_i$ [solar]	$K_i$	$\chi^2/\text{dof}$
0.5–10 keV	1	9.7(8.6–10.4)	0.33(0.31–0.36)	$1.07(0.88 - 1.13) \times 10^{-2}$	1295.0/1207
	2	> 32.5	= $Z_1$	$3.73(3.01 - 5.39) \times 10^{-3}$	
4.0–5.5 keV	1	9.8(3.6–11.6)	0.35(0.28–0.52)	$9.2(2.9 - 14.1) \times 10^{-3}$	185.2/159
	2	34.4(> 22.2)	= $Z_1$	$4.67(0.26 - 1.07) \times 10^{-3}$	



**Fig. 4.** (a) Two-temperature APEC model fit to the observed XIS spectra. The spectra taken by four sensors, XIS-0 (black), 1 (red), 2 (green), and 3 (blue), are shown separately. The solid lines in the upper panel show the sum of two APEC models with different temperatures, while the dashed lines show the low-temperature (upper curves) and high-temperature (lower curves) components separately, convolved with the telescope and the detector response functions. In the bottom panel the residuals of the fit in units of the number of standard deviations are shown. (b) Blow-up of the XIS spectra in the 4–5.5 keV band. The two-temperature model fits both the He-like and H-like Fe  $\text{K}\alpha$  lines adequately.

#### 4. HXD/PIN analysis: 12–60 keV

For the PIN diodes of HXD working in the energy band of 12–60 keV, the background is composed of the following three components: (i) the non-X-ray background (NXB), (ii) Cosmic X-ray Background (CXB), and (iii) bright point-like sources within the detector field of views. Of these, the NXB dominates the observed flux particularly for faint hard X-ray sources such as clusters of galaxies.

Since the NXB has a significant time-variability, the reproducibility of the NXB is the most important factor in the measurements of the hard X-ray flux from clusters of galaxies. In § 4.1 the systematic error due to NXB is carefully examined. In § 4.2 the CXB model is calculated. In § 4.3 the point source fluxes are estimated from the *XMM-Newton* observations of the same field.

##### 4.1. Non-X-ray background

The latest report from the instrument team<sup>4</sup> shows that the reproducibility of the PIN NXB model for the data that have been processed with the version 2 pipeline was typically 3% ( $1\sigma$ ). This estimate is based upon systematic comparisons between the NXB model and the PIN data during the Earth occultation in a trend archive. We check below the validity of assigning the 3% systematic error to our PIN analysis.

In Fig. 5 we show comparisons between the observed PIN data (hereafter “Data”) and the NXB model in two observing periods, (a) Seq: 801013010, and (b) Seq: 801013020. In Table 5 we summarize the count rates in the 12–40 keV and 40–60 keV bands. The excess signal has been detected in Data–NXB at en-

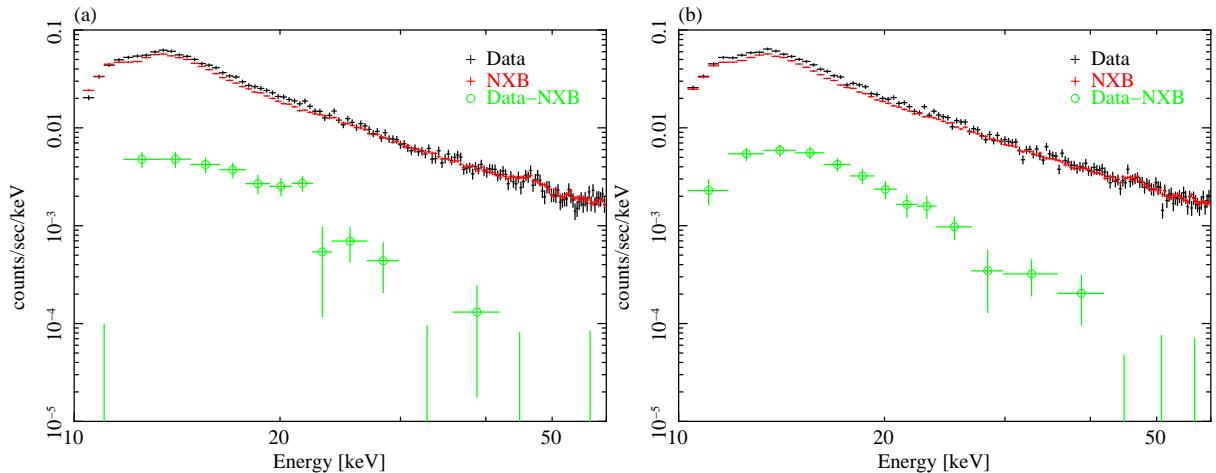
ergies below 30 keV during both observing periods. The difference in Data–NXB between two observing periods is well below the NXB itself:  $(\text{Data} - \text{NXB})_2 - (\text{Data} - \text{NXB})_1 \sim 0.02(\text{NXB}_1 + \text{NXB}_2)/2$ . However, the difference is marginally ( $\sim 2\sigma$ ) inconsistent with zero compared to its statistical error:  $(\text{Data} - \text{NXB})_2 - (\text{Data} - \text{NXB})_1 = 0.0088 \pm 0.0043$ , which could be indicative of some residual time variability.

In general, the NXB intensity changes depending primarily on the satellite’s passage of the SAA and the COR (Kokubun et al. 2007). To study these effects, we bin the PIN spectra under the following different conditions: elapsed time after the passage of the SAA,  $\text{TSAA} \gtrless 6000$  s, and three different COR [GV] ranges,  $6 < \text{COR} < 10$ ,  $10 < \text{COR} < 12$ ,  $12 < \text{COR} < 14$ . This analysis shows that there is a trend to obtain a higher count rate for  $\text{TSAA} < 6000$  s compared to  $\text{TSAA} > 6000$  s, and a higher count rate for a smaller COR. However, the differences in the count rates are below  $\pm 3\%$  of the NXB intensity in each case.

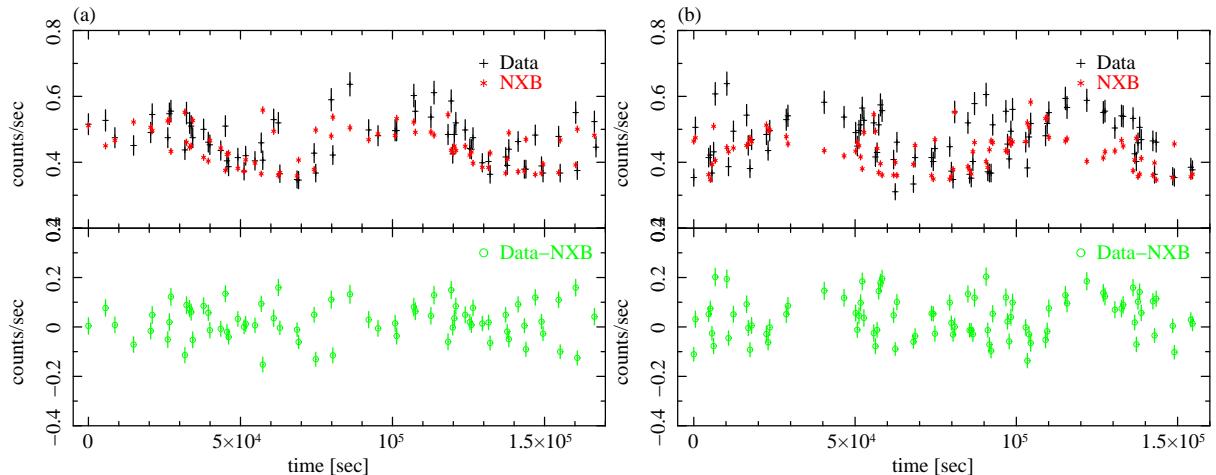
In order to study the reproducibility of the NXB further, a comparison was made for Data and NXB during the periods of the Earth occultation. The Earth is known to be dark in hard X-rays and the Earth occultation data can be regarded as NXB for the PIN observations. As a result, Data and NXB during the Earth occultation show a good agreement, and Data–NXB is consistent with zero. From these studies we conclude that the systematic error of the NXB model is fairly small ( $\lesssim 1\%$ ).

In summary, the accuracy of the PIN NXB model is consistent with that found in the latest report from the instrument team. Therefore, we shall adopt the instrument team’s estimate of the systematic error, 3%, and propagate it through our spectral analysis of the HXD/PIN data.

<sup>4</sup> JX-ISAS-SUZAKU-MEMO-2007-09 by Mizuno et al.



**Fig. 5.** Observed PIN spectra during two observing periods of RX J1347.5–1145. (a) Seq: 801013010, and (b) Seq: 801013020. In each panel Data, NXB, and (Data–NXB) are shown with the black crosses, red crosses, and green circles, respectively.



**Fig. 6.** Observed light curves of the PIN 12–40 keV count rates during two observing periods. (a) Seq: 801013010, and (b) Seq: 801013020. In the upper panels the Data and NXB rates are shown with the black and red crosses, respectively. In the bottom panels (Data–NXB) is shown with the green circles. The error bars show the  $1\sigma$  statistical errors.

**Table 5.** PIN count rates measured in the 12–40 keV and 40–60 keV bands. The quoted errors are  $1\sigma$  statistical errors.

Seq	Energy range	Exposure [s]	Data [ $\text{c s}^{-1}$ ]	NXB [ $\text{c s}^{-1}$ ]	(Data–NXB) [ $\text{c s}^{-1}$ ]	(Data–NXB)/NXB %
801013010	12–40 keV	56698	$0.5180 \pm 0.0030$	$0.4754 \pm 0.0009$	$0.0426 \pm 0.0031$	$8.96 \pm 0.67$
801013020	12–40 keV	64922	$0.5223 \pm 0.0028$	$0.4709 \pm 0.0008$	$0.0514 \pm 0.0030$	$10.92 \pm 0.63$
801013010+801013020	12–40 keV	121620	$0.5203 \pm 0.0021$	$0.4730 \pm 0.0006$	$0.0473 \pm 0.0022$	$10.00 \pm 0.46$
801013010	40–60 keV	56698	$0.0497 \pm 0.0009$	$0.0499 \pm 0.0003$	$-0.0002 \pm 0.0010$	$-0.44 \pm 1.96$
801013020	40–60 keV	64922	$0.0497 \pm 0.0009$	$0.0495 \pm 0.0003$	$0.0002 \pm 0.0009$	$0.43 \pm 1.85$
801013010+801013020	40–60 keV	121620	$0.0497 \pm 0.0006$	$0.0497 \pm 0.0002$	$0.0000 \pm 0.0007$	$0.03 \pm 1.35$

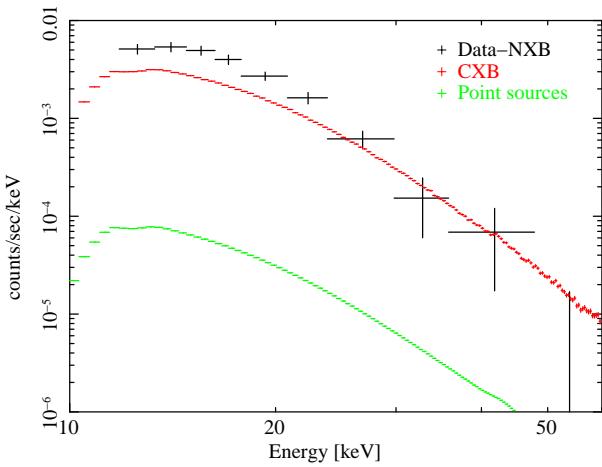
#### 4.2. Cosmic X-ray Background

We calculate the CXB spectrum in the PIN band assuming a power-law model with an exponential cut-off at 40 keV as previously reported from the *HEAO-1* A2 (Boldt 1987). Since the PIN detector response assumes a uniform distribution of emission over  $2^\circ \times 2^\circ$  on the sky, the CXB model for 4 square degree field in units of photons  $\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$  is given by

$$\frac{dN}{dE} = 9.412 \times 10^{-3} \left( \frac{E}{1 \text{ keV}} \right)^{-1.29} \exp\left(-\frac{E}{40 \text{ keV}}\right). \quad (1)$$

The 20–50 keV energy flux of the CXB model (Eq. 1),  $5.8 \times 10^{-8} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$ , agrees with the recent report from the *Beppo-SAX* observations (Frontera et al. 2007) within about 8%. This level of uncertainty in the CXB model is smaller than the systematic error of the current NXB model. However, according to the calibration report based on the Crab observations, the PIN spectral normalization is systematically higher than the previous results given in Toor & Seward (1974) by 13%. Thus, we increase CXB given in Eq. 1 by a factor of 1.13 in the simulation.

The resulting simulated CXB spectrum is shown in Fig. 7. To calculate the CXB spectrum the integration time of 100 Ms



**Fig. 7.** Observed PIN spectrum minus the nominal NXB model (Data–NXB; black), the simulated CXB model (red), and the point source contribution estimated from the *XMM-Newton* observations of the same field (green).

was assumed; thus, the statistical error of the simulated spectrum is negligibly small. The CXB count rates in the 12–40 keV and 40–60 keV bands are given by  $2.9 \times 10^{-2}$  and  $6.1 \times 10^{-4}$  c s $^{-1}$ , respectively, which amount to about 6.1% and 1.2% of the NXB, respectively.

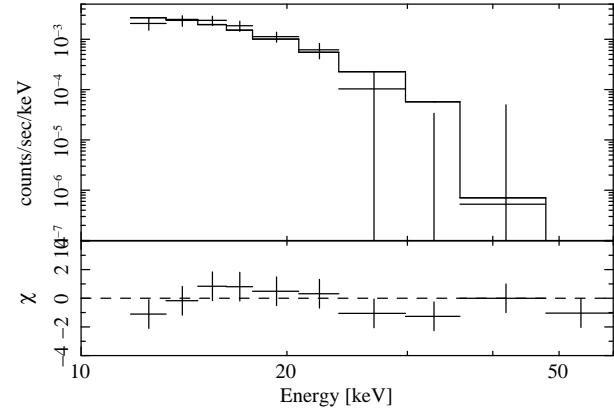
Kushino et al. (2002) have found that, based upon the *ASCA* observations, the CXB fluctuation in the 2–10 keV band is  $\sim 6\%$ , which can be attributed to the Poisson noise of the source count within 0.5 degree $^2$ . Moreover, by scaling the *HEAO-1* result of 2.8% with the equation  $\sigma_{\text{CXB}} \propto \Omega^{-0.5} S^{0.25}$  ( $\Omega$  and  $S$  are the effective solid angle of the observation and upper cut-off flux of detectable discrete sources in the field of view, respectively; Condon 1974), Kawano et al. (2008) calculated the 1 $\sigma$  fluctuation of CXB to be 9.2% for the  $\sim 100$  ks HXD/PIN observations. Therefore, the CXB fluctuation over the 30' scale is small compared to the NXB systematic error.

#### 4.3. Hard X-ray point sources

Next, we estimate the hard X-ray flux of point sources inside the field of view of HXD/PIN from the 30 ks *XMM-Newton*/PN data on the same field (Observation ID: 0112960101). The data reduction was carried out in the standard manner with SAS version 7.1.0 and the periods of background flares were removed with the threshold value of 0.22 c s $^{-1}$  in the 12–14 keV band.

With the `edetect_chain` program, thirty point sources have been detected in the PN image. The photon index for each source was estimated from the hardness ratio, defined as a ratio of the source count rates in the 0.5–1.5 keV and 1.5–5 keV band. The background was subtracted using the blank-sky data (Carter & Read 2007). The galactic absorption was assumed in the calculation. The photon index of  $\Gamma \gtrsim 2$  was obtained for almost all the sources that have significant emission in the hard band. We then simulate the PIN spectrum expected for each source using a power-law spectrum with  $\Gamma = 2$ , where we include the PIN angular response function using `hxdrarfgen`.

Fig. 7 shows the spectrum of the sum of the detected sources. We find that the contribution from the point sources is totally negligible.



**Fig. 8.** Observed PIN spectrum with the background model subtracted (Data–NXB–CXB; the crosses) in the 12–60 keV band. The error-bars show only the statistical errors. The histogram shows the best-fitting APEC thermal plasma model. The bottom panel shows the residuals in units of the number of standard deviations.

#### 4.4. PIN source spectrum

In Fig. 8 the observed PIN spectrum with NXB and CXB subtracted is shown. In the 12–40 keV band we detect the hard X-ray emission at the 9 $\sigma$  level. Taking into account the NXB systematic error, however, significance of the detection becomes much lower: the estimated count rate is  $0.0187 \pm 0.0021$  ( $\pm 0.0142$ ) c s $^{-1}$  in the 12–40 keV, where the first and second errors are the 1 $\sigma$  statistical and 1 $\sigma$  systematic uncertainties, respectively. At higher energies, 40–60 keV, the count rate is  $7 \pm 6$  ( $\pm 15$ )  $\times 10^{-4}$  c s $^{-1}$  (1 $\sigma$ ); thus, we do not expect significant hard X-ray emission in the 40–60 keV band.

Next, we fit the single-temperature APEC model to the background-subtracted PIN spectrum in the 12–60 keV band. (The XIS data is not used here. For a joint analysis of XIS and HXD/PIN, see § 5.) The metal abundance was fixed at the best-fitting value obtained from the XIS analysis, 0.33 solar. The systematic error of the spectral parameters due to the systematic uncertainty in the NXB model was estimated by changing the normalization factor of the NXB model by  $\pm 3\%$  and repeating the fitting procedure.

The results are shown in Fig. 8 and Table 6. We find that the temperature and normalization of the single-temperature APEC model are  $kT = 20.2^{+21.4}_{-8.0}$  ( $^{+7.7}_{-8.7}$ ) keV and  $1.02^{+0.95}_{-0.43}$  ( $^{+0.26}_{-0.26}$ )  $\times 10^{-2}$ , respectively. These parameters are consistent with those obtained from the XIS data. Therefore, we conclude that the hard X-ray emission observed with PIN does indeed come from RX J1347.5–1145.

From the observed PIN count rate and the best-fitting single-temperature APEC model given in Table 2, we estimate the energy flux to be  $3.8 \pm 0.5$  ( $\pm 3.3$ )  $\times 10^{-12}$  erg s $^{-1}$  cm $^{-2}$  in the 12–60 keV (1 $\sigma$ ). On the other hand, the previous *Beppo-SAX* observation of RX J1347.5–1145 has reported detection of the hard X-ray emission at the  $\sim 1.5\sigma$  significance:  $(4.0 \pm 2.6) \times 10^{-2}$  c s $^{-1}$  in the 13–60 keV band (Ettori et al. 2001), and  $(6.8 \pm 4.4) \times 10^{-2}$  c s $^{-1}$  in the 20–80 keV band (Nevalainen et al. 2004). With the 12.9 keV Raymond-Smith model and the response of the PDS instrument on board *Beppo-SAX*, the `pimms` program gives the 12–60 keV flux as  $(4.5 \pm 2.9) \times 10^{-12}$  erg s cm $^{-2}$ . (All errors quoted here are 1 $\sigma$ .) Thus, the PIN result agrees with that of PDS to within the 1 $\sigma$  errors.

**Table 6.** Single-temperature APEC model parameters fit to the PIN data in the 12–60 keV band. The systematic error in the NXB model is included in the error estimate.

Sensor	$kT$ [keV]	$Z$ [solar]	$K$	$\chi^2/\text{dof}$	NXB <sup>a</sup>
PIN	20.2 (12.2 – 41.6)	0.33(Fix)	$1.02(0.59–1.97)\times 10^{-2}$	6.7/8	1.00
PIN	11.5	0.33(Fix)	$0.76 \times 10^{-2}$	26.2/8	1.03
PIN	27.9	0.33(Fix)	$1.28 \times 10^{-2}$	6.9/8	0.97

<sup>a</sup> The NXB normalization factor.

## 5. XIS+HXD joint analysis

In § 3 the *Suzaku* XIS data indicated the presence of a significant amount of very hot gas. In this section, we study the physical properties of this hot component, such as the amount, temperature, and metal abundance, by performing a joint analysis of the *Suzaku* data and the spatially-resolved *Chandra* spectra.

In § 5.1 the properties of the ambient gas are derived from the *Chandra* data. In § 5.2 the properties of the hot gas component in the SE quadrant are derived from the *Suzaku* broad-band spectra combined with the *Chandra* data by means of a multi-temperature model. In § 5.3 we argue that the hot component is explained better by thermal gas than by non-thermal gas, and derive an upper limit on the possible non-thermal emission.

### 5.1. Modeling the cluster average component with *Chandra*

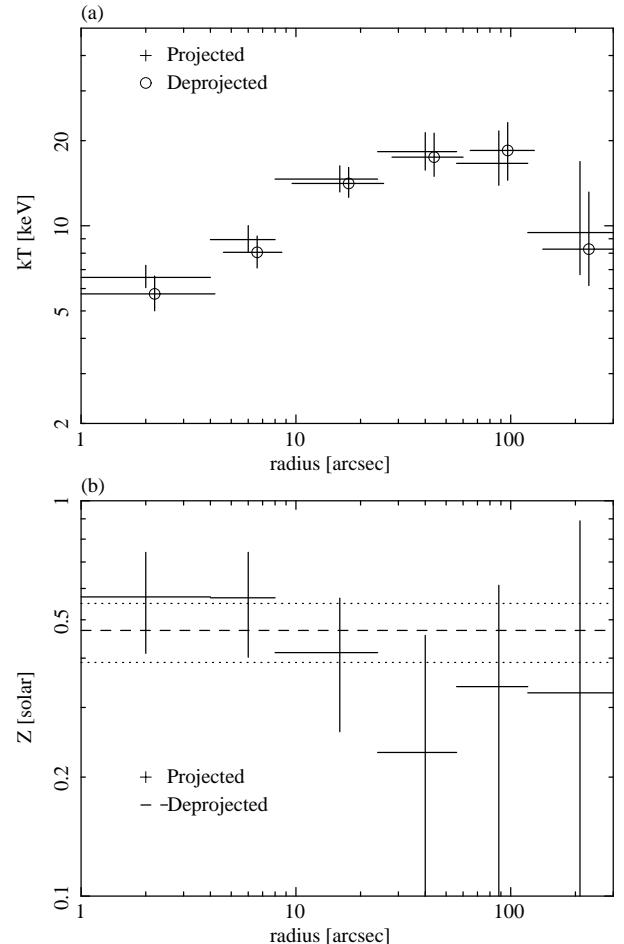
The deep *Chandra* ACIS-I data on RX J1347.5–1145 (Obs ID:3592, Date:2003-09-03) was analyzed with CIAO version 3.4 and CALDB version 3.3.0. The net exposure time after removing the periods of high background rates is 56.1 ks. The backgrounds were estimated from the same detector regions of the blank-sky data, whose normalization factors were determined with the ratios of the 10–12 keV count rates.

Fig. 9 shows the *Chandra* image and the azimuthally-averaged surface brightness profiles for three different position angles ( $0^\circ$  –  $360^\circ$ , NW:  $-90^\circ$  –  $180^\circ$ , and SE:  $180^\circ$  –  $270^\circ$ ). The cluster emission extends out to  $r = 5' \sim 1.7$  Mpc and the significant excess emission is visible in  $10'' \lesssim r \lesssim 60''$  for the SE quadrant.

To derive the average temperature profile within  $5'$ , we measure the spectra in the following six radial bins in the NW region, i.e., the region outside of the SE quadrant:  $0$  –  $4''$ ,  $4''$  –  $8''$ ,  $8''$  –  $24''$ ,  $24''$  –  $56''$ ,  $56''$  –  $120''$ , and  $120''$  –  $300''$ . The radial bins were chosen such that the temperature profile is measured with sufficient spatial resolution and the statistical accuracy  $\sim 20\%$ .

Fig. 10 shows the projected temperature profile, i.e., the temperature profile determined from the simple APEC model fit to each radial bin in the NW region. Our estimate of the projected temperature profile derived from the *Chandra* ACIS-I data agrees with the previous *Chandra* ACIS-S results reported by Allen et al. (2002) to within the statistical error, particularly in the central  $100''$  region. We have also confirmed based on the ACIS-I spectral simulations assuming the same photon statistics as the present observation that we can securely determine the temperature of each bin including the high-temperature ( $\sim 18$  keV) regions between  $24''$  and  $120''$ .

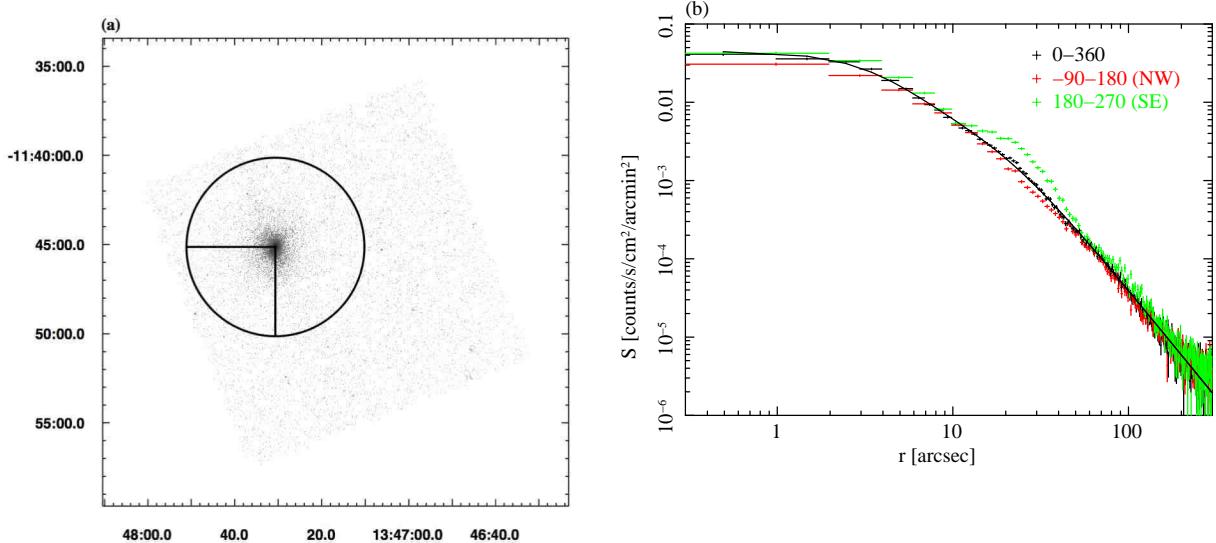
Since each spectrum is a superposition of the cluster emission from any points along the line of sight, we correct this effect, or “deproject,” by using the PROJCT model in the XSPEC software and fitting the six radial bins simultaneously under the assumption that the temperature distribution is spherically symmetric. As noted in Allen et al. (2002), the metal abundance gra-



**Fig. 10.** (a) Projected (crosses) and deprojected (circles) temperature profiles measured from the *Chandra* data in the NW region. (b) Projected metal abundance profile (crosses). The horizontal dashed and dotted lines show the best-fitting constant abundance and the corresponding 90% confidence interval obtained from the deprojection analysis, respectively. We shall assume that the metal abundance is constant over all radial bins throughout this paper.

dient is marginally seen in the *Chandra* data; however, the large uncertainty in the metal abundance measurement does not warrant our treating it as a free function. We therefore assume that the metal abundance distribution is uniform and ignore the abundance gradient.

The resulting deprojected temperature profile in the NW region is shown in Fig. 10 and the best-fitting parameters are given in Table 7. Henceforth, we refer to the best-fitting model presented in Table 7 as the “6APEC model.”



**Fig. 9.** (a) *Chandra* ACIS-I image in the 0.5–7 keV band. The solid lines show the NW and SE regions. The radius of the circle is 5''. (b) The surface brightness profiles of the position angle 0° – 360° (black), NW:–90° – 180° (red), and SE:180° – 270° (green). The black line shows the best-fitting double  $\beta$ -model for the position angle of 0° – 360°.

**Table 7.** Parameters of the “6APEC model,” estimates of the deprojected temperature profile from the *Chandra* ACIS-I data at the six annular bins in the NW region, which excludes the SE quadrant.

Radius ["]	$kT$ [keV]	$Z$ [solar] <sup>a</sup>	$K$ <sup>b</sup>	$\chi^2/\text{dof}$
0–4	5.74 (5.01 – 6.64)	0.47 (0.39 – 0.55)	$0.97(0.92 – 1.02) \times 10^{-3}$	364.2/290
4–8	8.06 (7.10 – 9.20)		$1.83(1.77 – 1.89) \times 10^{-3}$	
8–24	14.12 (12.61 – 16.08)		$4.02(3.93 – 4.10) \times 10^{-3}$	
24–56	17.49 (14.95 – 21.26)		$2.86(2.79 – 2.95) \times 10^{-3}$	
56–120	18.47 (14.49 – 23.18)		$2.29(2.22 – 2.37) \times 10^{-3}$	
120–300	8.27 (6.15 – 13.16)		$0.91(0.86 – 0.97) \times 10^{-3}$	

<sup>a</sup> The metal abundance is assumed to be common for all radial bins.

<sup>b</sup>  $K$  represents the normalization factor for each spherical shell, i.e., the position angle of 0° – 360°, of the fitting.

## 5.2. Temperature measurement of the SE clump

The 6APEC model in § 5.1 describes the average temperature structure of ambient gas, measured from the NW region. We subtract the flux accounted by this model from the *Suzaku* data, and study the nature of the excess emission in the SE quadrant.

We add another APEC model to describe the hot component in the SE quadrant. We use the best-fitting parameters for  $kT$  and  $K$  given in Table 7 for the ambient gas (6APEC model), and use the *Suzaku* data, both the XIS and PIN spectra, to constrain the temperature,  $kT_{\text{ex}}$ , and the normalization,  $K_{\text{ex}}$ , of the excess component in the SE quadrant. As for the metal abundance, the abundance is assumed to be equal to all of the six radial bins of the ambient gas, as well as to the excess component, i.e., a single abundance is applied to the entire cluster. We do this because the metal abundance is not constrained by the *Chandra* data very well.

We have found that the *Chandra* data tend to give systematically higher values for  $kT$  and  $K$  than the XIS data do. In order to correct for the difference between their instrumental calibrations, we multiply the 6APEC model by the PLABS model,  $M(E) = E^{-\alpha}$ , with  $\alpha = 0.02$  ( $E$  is the energy of photons), and use the relative normalization factor of 0.93. See Appendix A for more details on the *Suzaku-Chandra* cross-calibration.

Fig. 11 and Table 8 show the results of the 6APEC×PLABS + APEC model fit to the XIS (0.5–10 keV) and PIN (12–60 keV)

data. To show the degree of systematic errors due to the uncertainty in the *Suzaku-Chandra* cross-calibration, we also show the parameters for  $\alpha = 0$  and 0.03 in Table 8. From these results we conclude that the temperature of the excess emission in the SE quadrant is  $kT_{\text{ex}} = 25.3^{+6.1}_{-4.5} ({}^{+6.9}_{-9.5})$  keV, where the first error is statistical and the latter is systematic (both 90% C.L.). In Table 8, we also show the fitted parameters when only XIS was used. Thanks to the high photon statistics of XIS, the temperature of the SE excess component can be constrained as  $kT_{\text{ex}}^{\text{XIS}} = 24.8^{+6.1}_{-4.6} ({}^{+6.8}_{-9.5})$  keV. However, the spectral cut-off at  $25/(1+z) \sim 17$  keV actually falls into the PIN band, which suggests the importance of the broad-band spectroscopy in the present study. As for the other quantities, we find from the XIS+PIN joint analysis that the metal abundance is 0.38(0.35–0.41) solar, and the absorption-corrected X-ray luminosity of the excess component is  $L_{\text{X,ex}} = 1.4 \times 10^{45}$  erg s<sup>–1</sup> in the 0.5–10 keV, and  $1.2 \times 10^{45}$  erg s<sup>–1</sup> in the 12–60 keV.

Since the determination of  $kT_{\text{ex}}$  from the X-ray spectroscopy is the central result of this paper, we estimate the other potential source of systematic errors in our analysis. Specifically, we examine: (i) the assumption of constant metal abundance over all radii, (ii) some arbitrariness in the choice of the SE region, and (iii) effects of the uncertainty in the 6APEC model parameters.

- (i) What if the metal abundance of the ambient gas and that of the excess component are different? What if the abun-

**Table 8.** Spectral parameters for the SE excess component obtained from the 6APEC $\times$ PLABS+APEC model fit to the XIS+PIN data and the XIS data.

Sensor	APEC			$\chi^2/\text{dof}$	$\alpha^b$
	$kT_{\text{ex}}$ [keV]	$Z_{\text{ex}}$ [solar] <sup>a</sup>	$K_{\text{ex}}$		
XIS0–3+PIN	25.3(20.8–31.4)	0.38(0.35–0.41)	$2.14(2.05–2.24)\times 10^{-3}$	1311.1/1219	0.02
XIS0–3+PIN	15.8	0.36	$1.98\times 10^{-3}$	1313.1/1219	0.00
XIS0–3+PIN	32.2	0.39	$2.26\times 10^{-3}$	1310.2/1219	0.03
XIS0–3	24.8(20.2–30.9)	0.38(0.35–0.41)	$2.00(1.91–2.09)\times 10^{-3}$	1303.3/1209	0.02
XIS0–3	15.5	0.36	$1.84\times 10^{-3}$	1303.7/1209	0.00
XIS0–3	31.9	0.39	$2.11\times 10^{-3}$	1303.0/1209	0.03

<sup>a</sup> The metal abundance is assumed to be the same for all the APEC components, including the ambient gas as well as the excess component.

<sup>b</sup> The power-law index of the PLABS model, coming from the *Suzaku-Chandra* cross-calibration (see text).

dance gradient does exist in the ambient gas? To explore these possibilities we treat the metal abundance of the excess component,  $Z_{\text{ex}}$ , as well as that of the ambient gas in two larger radial bins,  $0'' < r < 8''$  and  $8'' < r < 300''$ , as free parameters, and fit them simultaneously. We find  $kT_{\text{ex}} = 26.3$  keV,  $Z_{\text{ex}} < 1.8$  solar, and  $K_{\text{ex}} = 2.16 \times 10^{-3}$  ( $\chi^2/\text{dof} = 1306/1217$ ), which are consistent with the values given in Table 8. As for the metal abundance of the ambient gas we find  $Z \sim 0.64$  solar and 0.22 solar in  $0'' < r < 8''$  and  $8'' < r < 300''$ , respectively.

- (ii) From the *Chandra* image one may observe that the excess emission appears to extend over slightly more than the SE quadrant. How does this affect the determination of  $kT_{\text{ex}}$ ? We repeat our analysis with the SE and NW regions re-defined as  $(180^\circ - 315^\circ)$  and  $(-45^\circ - 180^\circ)$ , respectively. We find  $kT_{\text{ex}} = 20.0$  keV,  $K_{\text{ex}} = 2.87 \times 10^{-3}$ , and  $Z_{\text{ex}} = Z = 0.37$  solar with  $\chi^2/\text{dof} = 1315/1219$ . Therefore, the exact choice of the SE region does not change the best-fitting parameters very much.
- (iii) The statistical errors in the 6APEC model parameters had not been propagated through the spectral fitting of the SE quadrant, except for the cross-calibration error in the spectral slope, which was included by varying  $\alpha$  from 0 to 0.03. To address this, we carry out simultaneous APEC fits to the *Chandra* spectra in 6 radial bins (without deprojection) as well as to the *Suzaku* XIS and PIN spectra, for which we use the 6 APEC models multiplied by the  $\alpha = 0.02$  PLABS model plus the additional APEC model. We find  $kT_{\text{ex}} > 26$  keV,  $Z_{\text{ex}} = 0.38(0.35 - 0.41)$  solar, and  $K_{\text{ex}} = 2.16(1.96 - 2.41) \times 10^{-3}$  ( $\chi^2/\text{dof} = 1676/1510$ ). Although the temperature is not well constrained in this case, it equally shows a high value.

From these studies we conclude that our estimate,  $kT_{\text{ex}} = 25.3^{+6.1}_{-4.5} ({}^{+6.9}_{-9.5})$  keV, is robust.

Finally, as a consistency check we analyze the *Chandra* spectrum of the SE quadrant ( $r < 5'$ ) on its own, without the *Suzaku* data, in the same manner. The best-fitting parameters for the excess component are  $kT_{\text{ex}}^{\text{Chandra}} = 31.1^{+24.1}_{-12.6}$  keV,  $Z_{\text{ex}}^{\text{Chandra}} = 0.49^{+0.15}_{-0.15}$  solar, and  $K_{\text{ex}}^{\text{Chandra}} = 1.47^{+0.21}_{-0.15} \times 10^{-3}$  ( $\chi^2/\text{dof} = 320/332$ ). Therefore, both the *Chandra*-alone analysis and the joint *Chandra+Suzaku* analysis show that the excess emission has the temperature in excess of 20 keV.<sup>5</sup>

<sup>5</sup> As for the normalization factor,  $K_{\text{ex}}^{\text{Chandra}}$  is found to be smaller than that from the joint analysis by about 35%. This may be explained by the difference in their integration regions. On the other hand, this level of difference actually amounts only to a few% of the total cluster emis-

Compared to the results from the *Chandra* data alone, the joint *Chandra+Suzaku* broad-band data analysis yields much more accurate determination of  $kT_{\text{ex}}$ . The *Suzaku*'s unprecedented sensitivity over the wide X-ray band makes it possible to determine, for the first time, the temperature of such hot gas in the ICM solely from the X-ray spectroscopy without help of the SZ effect.

### 5.3. Constraint on the non-thermal emission

So far, we have been assuming that the excess hard X-ray emission from the SE quadrant is thermal; however, could it actually be non-thermal? If so, our derived temperature must be reconsidered.

To address this question, the XIS and PIN data is re-analyzed in light of non-thermal emission. While the 6APEC thermal plasma model is again used for the ambient gas, the APEC model is replaced with a power-law (PL) spectrum for describing the excess component. We then fit the new model, “6APEC $\times$ PLABS+PL model,” to the observed XIS and PIN data. The amplitude (normalization), a power-law index,  $\Gamma$ , of the non-thermal component, and the metal abundance of the ambient gas are treated as free parameters.

Fig. 12 shows the results, and Table 9 lists the best-fitting parameters. We find that the power-law index is given by  $\Gamma \sim 1.5$ , or more precisely  $\Gamma = 1.45^{+0.03}_{-0.04} ({}^{+0.09}_{-0.04})$ . The reduced  $\chi^2$  of this model,  $\chi^2 = 1317.1/1219$  (see Table 9), is slightly larger than that for the thermal model,  $\chi^2 = 1315.1/1219$  (see Table 8), and negative residuals are seen in consecutive bins above 22 keV.

Let us examine the non-thermal model more closely. In the XIS band below 10 keV, the non-thermal model with  $\Gamma = 1.5$  and the thermal APEC model with 25 keV are hardly distinguishable. However, the observed PIN spectrum is much *softer* than  $\Gamma = 1.5$ , with the effective photon index being  $\Gamma_{\text{eff}} \sim 3$ . When we fit the 6APEC $\times$ PLABS+PL model to the PIN data alone, the 90% lower bound on the photon index is found as  $\Gamma > 1.8^6$ , which is significantly above the 90% upper bound on  $\Gamma$  from the XIS data,  $\Gamma < 1.5$ . We have further checked that fixing the power-law index to  $\Gamma = 2.0$ , as predicted from the non-thermal bremsstrahlung in the strong shock limit (Sarazin & Kempner 2000), yields a poor fit to the XIS and PIN data; the reduced  $\chi^2$  is 1708 for 1220 degrees of freedom. Therefore, it seems difficult

sion, and is comparable to the calibration errors of the instruments. Therefore, we simply assign 30% systematic error to  $K_{\text{ex}}$ .

<sup>6</sup> The systematic errors due to both the NXB model and the *Suzaku-Chandra* cross-calibration are included.

**Table 9.** Spectral parameters for the SE excess component obtained from the 6APEC $\times$ PLABS+non-thermal power-law (PL) model fit to the XIS+PIN data.

Sensor	Power-law		6APEC		
	$\Gamma$	Normalization	Z [solar]	$\chi^2/\text{dof}$	$\alpha$
XIS0–3+PIN	1.45(1.41–1.48)	$2.58(2.30–2.52)\times 10^{-4}$	0.42(0.39–0.45)	1317.1/1219	0.02
XIS0–3+PIN	1.54	$2.57\times 10^{-4}$	0.40	1312.5/1219	0.00
XIS0–3+PIN	1.41	$2.58\times 10^{-4}$	0.42	1321./1219	0.03

**Table 10.** Limits on the amplitude (normalization) of a non-thermal power-law (PL) component with  $\Gamma = 1.5$  as the explanation of the excess hard X-ray emission in the SE quadrant.

Sensor	Model <sup>a</sup>	Normalization <sup>b</sup>		$\chi^2/\text{dof}^c$		Flux(12–60 keV) <sup>d</sup> [erg s $^{-1}$ cm $^{-2}$ ]
		NXB $\times 1.00$	NXB $\times 0.97$	NXB $\times 1.00$	NXB $\times 0.97$	
PIN	APEC+PL	$\sim 0$	$5.1 \times 10^{-4}$	7.2/7	4.6/7	$< 2.11 \times 10^{-11}$
XIS0–3+PIN	APEC+PL	$< 1.6 \times 10^{-4}$	$2.0 \times 10^{-4}$	1310.2/1218	1344.3/1218	$< 8.2 \times 10^{-12}$
PIN	PL	$1.8(0.7–2.9) \times 10^{-4}$	$6.3 \times 10^{-4}$	8.8/9	5.1/9	$< 2.15 \times 10^{-11}$
XIS0–3+PIN	PL	$2.48(2.39–2.59) \times 10^{-4}$	$2.52 \times 10^{-4}$	1322.8/1220	1351.9/1220	$< 3.8 \times 10^{-12}$

<sup>a</sup> The spectral model for the SE excess emission.<sup>b</sup> The amplitude (normalization) of the power-law component after removing the NXB models with rescaling factors of 1 and 0.97. The error and limits are the  $1\sigma$  bound.<sup>c</sup> The values of  $\chi^2$  and the number of degrees of freedom.<sup>d</sup> The  $3\sigma$  upper limit on the energy flux of the power-law component in the 12–60 keV band.

to explain the SE excess component with the non-thermal PL model.

Given that the excess component is explained better by the thermal emission than by the non-thermal emission, we derive an upper limit on the non-thermal emission as the explanation for the SE component. We fix the metal abundance and the PL index at 0.38 solar and  $\Gamma = 1.5$ , respectively. The 6APEC model modified by the  $\alpha = 0.02$  PLABS model is again used for describing the ambient gas.

The derived upper limits are given in Table 10. Taking into account the NXB systematic error of the PIN detector, the  $3\sigma$  upper limit on the non-thermal flux in the 12–60 keV,  $F_{\text{HXR}}$ , is estimated as  $F_{\text{HXR}} < 2.1 \times 10^{-11}$  erg s $^{-1}$  cm $^{-2}$  from the PIN analysis, and  $F_{\text{HXR}} < 8 \times 10^{-12}$  erg s $^{-1}$  cm $^{-2}$  from the XIS+PIN simultaneous fit. Here,  $1\sigma$  error is calculated by adding the  $1\sigma$  statistical error and the  $1\sigma$  systematic error in quadrature.

## 6. Discussion

Using the deep broad-band observations of RX J1347.5–1145 with *Suzaku*, the temperature structure has been determined with a particular focus on the extremely hot gas. We have found that the multi-temperature thermal emission model including the very hot ( $kT_{\text{ex}} \sim 25$  keV) component fits the wide-band spectra well. We have also placed an upper limit on the non-thermal hard X-ray emission.

In § 6.1 our results are compared with the previous X-ray and radio observations, and examine the physical properties of the SE clump further. In § 6.2 our results are compared with the radio mini halo in this cluster that has been discovered from the 1.4 GHz radio observations to estimate the magnetic field strength in the ICM.

### 6.1. Properties of the extremely hot gas

From the analysis of the *Suzaku* spectra of RX J1347.5–1145, the temperature of the SE excess emission is obtained to be  $kT_{\text{ex}} = 25.3^{+6.1}_{-4.5} (^{+6.9}_{-9.5})$  keV (90% C.L.; the first error being sta-

tistical and the second systematic). This is in an excellent agreement with the previous measurement by Kitayama et al. (2004),  $28.5 \pm 7.3$  keV (68%; statistical only), from a joint analysis of the SZ data (Komatsu et al. 1999, 2001) and the *Chandra* ACIS-S3 data (Allen et al. 2002). Here, we compare our X-ray-only results with their SZ+X-ray results.

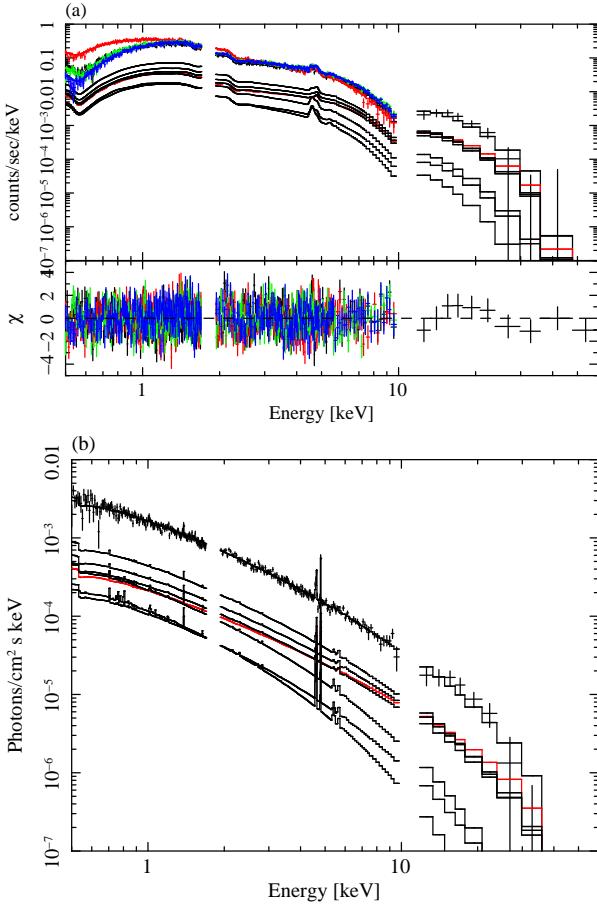
We estimate the gas density and gas mass of the SE excess component from the *Suzaku* and *Chandra* data. For simplicity, we assume that the extremely hot gas is uniformly distributed within a sphere of a radius  $R = 25'' \sim 144$  kpc (because the excess is present in  $10'' < r < 60''$ ; Fig. 9b). Using the measured spectral normalization,  $K_{\text{ex}}$ , which depends on  $n_{\text{e}} n_{\text{H}} V$  (where  $V = 4\pi R^3/3$  is the volume of the gas and  $n_{\text{H}} = 0.86 n_{\text{e}}$ ), the electron density,  $n_{\text{ex}}$ , and the gas mass,  $M_{\text{gas,ex}}$ , are obtained as:

$$n_{\text{e,ex}} = (1.6 \pm 0.2) \times 10^{-2} \left( \frac{V_{\text{ex}}}{3.6 \times 10^{71} \text{ cm}^3} \right)^{-1/2} \text{ cm}^{-3}, \quad (2)$$

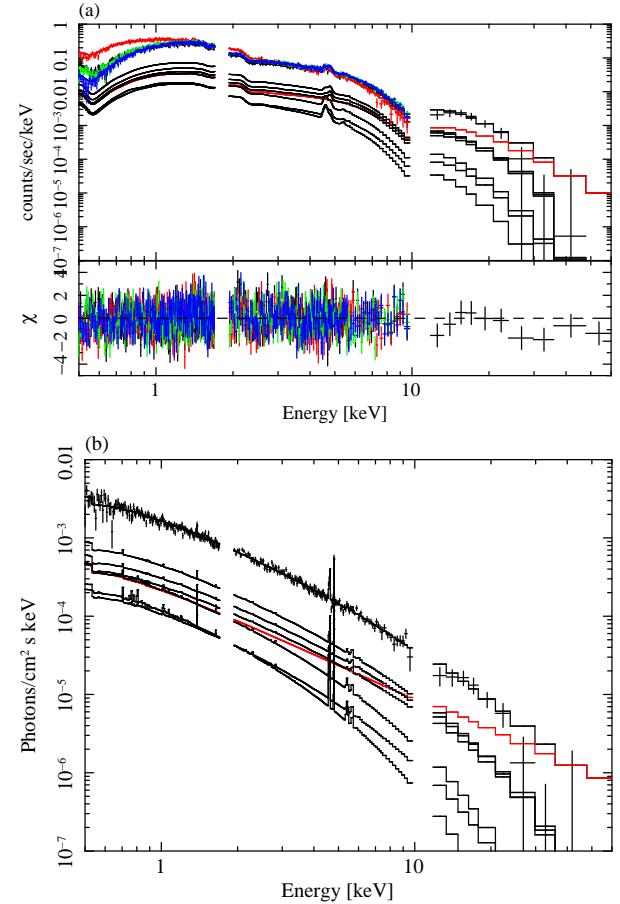
$$M_{\text{gas,ex}} = (5.6 \pm 0.8) \times 10^{12} \left( \frac{V_{\text{ex}}}{3.6 \times 10^{71} \text{ cm}^3} \right)^{1/2} \text{ M}_{\odot}. \quad (3)$$

Here, we have propagated the systematic error in  $K_{\text{ex}}$  through the final results (§ 5.2). These results may be compared with those obtained in Kitayama et al. (2004):  $n_{\text{ex}} = (1.49 \pm 0.59) \times 10^{-2}$  cm $^{-3}$  and  $M_{\text{gas,ex}} \sim 2 \times 10^{12}$  M $_{\odot}$ . While the inferred number densities are in an excellent agreement, the gas mass from our analysis is more than a factor of two greater than that from Kitayama et al. (2004); however, the uncertainty in the gas mass estimate from Kitayama et al. (2004) is large enough for them to be consistent. (The uncertainty is large because they did not assume spherical geometry for the excess component, and the line-of-sight extension of the SE component was poorly constrained.)

How does the excess component compare with the rest of the cluster? The average (ambient) temperature and gas density for  $10'' < r < 60''$ , excluding the SE quadrant, are  $kT \sim 15$  keV from the *Chandra* spectrum and  $n_{\text{e}} \sim 6.6 \times 10^{-3}$  cm $^{-3}$  from Eqs. 3–5 of Kitayama et al. (2004), respectively. Thus, the SE clump exhibits the temperature and the density that are higher than the ambient gas in the same radial bins by factors of 1.6 and 2.4, respectively. This means that the excess hot component



**Fig. 11.** (a) 6APEC $\times$ PLABS( $\alpha = 0.02$ ) + APEC model, fit simultaneously to the observed XIS (0.5–10 keV) and PIN (12–60 keV) spectra. The spectra taken by four sensors, XIS-0 (black), 1 (red), 2 (green), and 3 (blue), are shown separately. The black and red lines show the ambient component (6APEC $\times$ PLABS) and the excess hot component described by an additional APEC model, respectively, convolved with the telescope and the detector response functions. In the bottom panel the residuals of the fit in units of the number of standard deviations are shown. We have used the nominal NXB model for the background of the PIN data (see § 4.1). (b) same as (a), but for the unfolded XIS-0 and PIN spectra.



**Fig. 12.** (a) 6APEC $\times$ PLABS( $\alpha = 0.02$ ) (thermal model for the ambient gas) + PL model (non-thermal model for the hot gas), fit simultaneously to the observed XIS (0.5–10 keV) and PIN (12–60 keV) spectra. The spectra taken by four sensors, XIS-0 (black), 1 (red), 2 (green), and 3 (blue), are shown separately. The black and red lines show the ambient component (6APEC $\times$ PLABS) and the excess hot component described by a non-thermal power-law model, respectively, convolved with the telescope and the detector response functions. In the bottom panel the residuals of the fit in units of the number of standard deviations are shown. We have used the nominal NXB model for the background of the PIN data (see § 4.1). (b) same as (a), but for the unfolded XIS-0 and PIN spectra.

is over-pressured, and such a region is expected to be short-lived, ~0.5 Gyr (Takizawa 1999).

As already discussed in Kitayama et al. (2004), the gas properties can be explained by a fairly recent (within the last 0.5 Gyr or so), bullet-like high velocity ( $\Delta v \sim 4500 \text{ km s}^{-1}$ ) collision of two massive ( $5 \times 10^{14} \text{ M}_\odot$ ) clusters.

Moreover, the heat energy of the SE clump is estimated to be  $E_{\text{th,ex}} = (3/2)kT_{\text{ex}}(n_{e,\text{ex}} + n_{\text{H,ex}})V_{\text{ex}} \sim 6 \times 10^{62} \text{ erg}$ . This huge amount of energy cannot be easily produced by a central source in the cluster: one would need an AGN with  $10^{46} \text{ erg s}^{-1}$  for at least 1 Gyr and put the energy into the SE region without any radiative loss. On the other hand, cluster mergers, which are the most energetic events in the Universe after the Big Bang, will most naturally explain this high energy phenomenon. Therefore our results do support the merger scenario, solely from the X-ray spectroscopic data without help of the SZ data.

## 6.2. Estimation of the magnetic field

What physics can we learn from our upper limit on the non-thermal hard X-ray emission from the *Suzaku* HXD/PIN? The non-thermal hard X-ray emission is produced via the inverse Compton (IC) scattering of relativistic electrons off the Cosmic Microwave Background (CMB) photons, and the same population of electrons also produce the synchrotron radiation. From the exact derivations by Blumenthal & Gould (1970), equations for the synchrotron emission at the frequency  $\nu_{\text{Syn}}$  and the IC emission at  $\nu_{\text{IC}}$  are:

$$\frac{dW_{\text{Syn}}}{d\nu_{\text{Syn}} dt} = \frac{4\pi N_0 e^3 B^{(p+1)/2}}{m_e c^2} \left( \frac{3e}{4\pi m_e c} \right)^{-(p-1)/2} a(p) \nu_{\text{Syn}}^{-(p-1)/2}, \quad (4)$$

$$\frac{dW_{\text{IC}}}{d\nu_{\text{IC}} dt} = \frac{8\pi^2 r_0^2}{c^2} h^{-(p+3)/2} N_0 (k_B T_{\text{CMB}})^{(p+5)/2} F(p) \nu_{\text{IC}}^{-(p-1)/2}. \quad (5)$$

Here  $N_0$  and  $p$  are the normalization and the power-law index of the electron distribution,  $N(\gamma) = N_0\gamma^{-p}$  ( $\gamma$  is the Lorentz factor of the electron).  $h$  is the Planck constant,  $T_{\text{CMB}}$  is the CMB temperature and  $T_{\text{CMB}} = 2.73(1+z)$  K. The functions  $a(p)$  and  $F(p)$  are defined as follows:

$$a(p) = \frac{2^{(p-1)/2} \sqrt{3} \Gamma\left(\frac{3p-1}{12}\right) \Gamma\left(\frac{3p+19}{12}\right) \Gamma\left(\frac{p+5}{4}\right)}{8\pi^{1/2} (p+1) \Gamma\left(\frac{p+7}{4}\right)}, \quad (6)$$

$$F(p) = \frac{2^{p+3} (p^2 + 4p + 11)}{(p+3)^2 (p+5) (p+1)} \Gamma\left(\frac{p+5}{2}\right) \zeta\left(\frac{p+5}{2}\right). \quad (7)$$

Eqs. 4 and 5 give the total emitted powers per volume per frequency in the rest frame. Given that both powers are diminished by the same dimming factor, the ratio of observed flux densities of the synchrotron and IC emission,  $S_{\text{Syn}}/S_{\text{IC}}$ , is equal to  $(dW_{\text{Syn}}/d\nu_{\text{Syn}}dt)/(dW_{\text{IC}}/d\nu_{\text{IC}}dt)$ , and the strength of the magnetic field  $B$  can be directly estimated.

We find  $S_{\text{IC}} < 0.11 \mu\text{Jy}$  from our limit on the non-thermal hard X-ray emission for electrons with the IC emission energy (frequency) of 12 keV ( $\nu_{\text{IC}} = 2.9 \times 10^{18} (1+z)^{-1}$  Hz). As for  $S_{\text{Syn}}$ , Gitti et al. (2007a) discovered extended ( $\sim 500$  kpc) radio emission in RX J1347.5–1145 based on their low ( $18''$ ) resolution VLA observations and higher ( $2''$ ) resolution data in the VLA archive. They subtracted contribution of discrete radio sources and estimated the total flux density of the diffuse radio emission to be  $S_{\text{Syn}} = 25 \text{ mJy}$  at  $\nu_{\text{Syn}} = 1.4(1+z)^{-1}$  GHz. Combining these numbers with Eqs. (4) and (5), a lower bound on the magnetic field strength in the ICM is obtained as  $B > 0.007 \mu\text{G}$  for  $p = 2\Gamma - 1 = 2$ . The estimation is sensitive to the assumption of  $p$ : for example, in the case of  $p = 3$ ,  $B > 0.072 \mu\text{G}$ .

This limit, though weak, is consistent with typical values found in other clusters,  $B \sim 0.1 - 1 \mu\text{G}$ , based on the *RXTE* and *Beppo-SAX* observations (e.g., Rephaeli et al. 2008). Our result is also comparable to the recent *Suzaku* report on a merging cluster A3376 at  $z = 0.046$ ,  $B > 0.03 \mu\text{G}$  (Kawano et al. 2008). However, the previous measurements came mostly from nearby ( $z < 0.1$ ) clusters as well as from some medium-redshift clusters such as A2163 at  $z = 0.20$  (Rephaeli et al. 2006) and the Bullet cluster at  $z = 0.296$  (Petrosian et al. 2006). Our work provides a constraint on the cluster magnetic field strength at a higher redshift,  $z = 0.451$ .

## 7. Summary

We have reported on the results from the analysis of the *Suzaku* wide-band (0.5–10 keV with XIS and 12–60 keV with HXD/PIN) X-ray spectroscopic observations of the most luminous X-ray cluster, RX J1347.5–1145, at  $z = 0.451$ , in order to investigate the temperature structure of the ICM, signatures of a recent violent merger, as well as signatures of the non-thermal emission.

This cluster is known to contain a very hot gas clump that produces the excess emission on top of the ambient gas that follows more-or-less the conventional  $\beta$  model (Komatsu et al. 2001; Allen et al. 2002; Kitayama et al. 2004). The temperature of this gas clump has not been measured accurately from the previous X-ray spectroscopic observations, as their sensitivities degrade significantly beyond 10 keV.

The re-analysis of the *Chandra* data confirms the previous work, and yields a poor limit on the temperature of the excess hot component,  $kT_{\text{ex}}^{\text{Chandra}} = 31.1^{+24.1}_{-12.6}$  keV (90% C.L.; statistical). When the hard X-ray data from the *Suzaku* XIS spectra in the 0.5–10 keV region and the HXD/PIN data in the 12–60 keV

are combined with the *Chandra* data, we finally obtain a good measurement of the temperature,  $25.3^{+6.1}_{-4.5} (^{+6.9}_{-9.5})$  keV (90% C.L.; statistical and systematic), which is in an excellent agreement with that derived from the previous joint analysis of the SZ effect and X-ray imaging observations (Kitayama et al. 2004). We stress that this is the first time that the X-ray spectroscopic observations alone give a good handle on such a high temperature gas component, which is made possible by *Suzaku*’s unprecedented sensitivity over the wide X-ray band.

We have found that the broad-band X-ray spectrum is explained better by the thermal plasma model than by the non-thermal power-law model. Thus, the present result confirms the presence of the hottest *thermal* gas in the cluster. The most likely explanation for this phenomena is a recent violent merger with the collision velocity of  $\sim 4500$  km/s, similar to the one found in the Bullet cluster (Milosavljević et al. 2007; Springel & Farrar 2007; Mastropietro & Burkert 2007; Nusser 2008).

The upper bound on the non-thermal flux in the 12–60 keV band,  $F_{\text{HXR}} < 8 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ , yields, when combined with a recent discovery of the radio mini halo in this cluster by Gitti et al. (2007a), a lower bound on the ICM magnetic field strength,  $B > 0.007 \mu\text{G}$  for the electron index of 2. These constraints provide valuable information on the non-thermal nature of the cluster gas and the particle acceleration in a high-redshift universe. However, the accuracy of the present measurement of the hard X-ray emission is limited by the sensitivity of the instrument. Suppose that the magnetic field in RX J1347.5–1145 is comparable to that of the other clusters,  $B \sim 0.1 \mu\text{G}$ , a 50-fold higher sensitivity is required to detect non-thermal hard X-ray emission from this cluster. We expect that the future X-ray missions (e.g., *NeXT*; Takahashi et al. 2008) will determine the non-thermal X-ray flux accurately and draw a more complete picture.

Before the advent of the *Suzaku* satellite, it was difficult to measure the high-temperature ( $\gg 10$  keV) gas in the X-ray band reliably, due to the limited sensitivity. The present paper demonstrates the power of the broad-band X-ray spectroscopy in the study of gas heating due to the cluster merger, which is nicely complementary to the observations of the SZ effect. In the near future we expect the number of samples of merging clusters observed with *Suzaku* to increase rapidly, which would shed new light on the physics of violent mergers.

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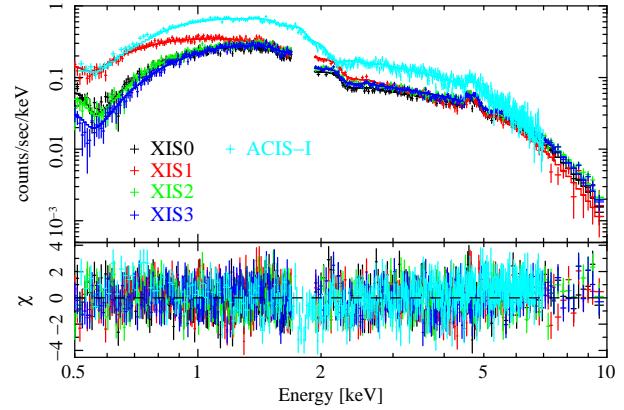
## Appendix A: The *Suzaku*-*Chandra* cross calibration

Because the temperature measurement of very hot gas based on the spectral fit is sensitive to a subtle change of the spectral slope, a precise calibration of the effective area is critical. In the analysis of XIS+HXD spectra (§5), we have modeled the cluster average emission with *Chandra*. Thus the cross-calibration between *Suzaku*/XIS and *Chandra*/ACIS-I is mandatory.

If the global cluster spectrum is accumulated from the  $r < 5'$  circular region with the *Chandra*/ACIS-I data, the APEC model fitting gave  $kT = 14.4(13.6 - 15.3)$  keV,  $Z = 0.45(0.38 - 0.52)$ ,  $K = 1.47(1.45 - 1.49) \times 10^{-2}$  ( $\chi^2/\text{dof} = 552.8/426$ ), where  $z = 0.451$  and  $N_{\text{H}} = 4.85 \times 10^{20} \text{ cm}^{-2}$  are adopted. In comparison with the best-fit XIS parameters (Table 2), the temperature and the normalization are higher by about 1.5 keV and 7% for *Chandra*. We discuss below the possible reasons in the light of the *Suzaku* and *Chandra* calibration uncertainties.

### 1. *Suzaku* XIS

Since the spatial extent of X-ray emission from RX J1347.5–1145 is small compared to the PSF of *Suzaku*, it can be treated as a point source (we have confirmed that the spectral fit with an auxiliary file generated for a point source at the HXD-nominal position yields statistically consistent spectral parameters with those listed in Table 2). According to the latest calibration of XIS and PIN, the best-fit power-law parameters describing the Crab spectra are the photon index  $\Gamma = 2.073 \pm 0.006$  and the normalization  $9.21 \pm 0.1 \text{ photons cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$ , which are by about 1.5% and 5%



**Fig. A.1.** *Suzaku*/XIS+*Chandra*/ACIS-I spectra of RX J1347.5–1145 ( $r < 5'$ ) simultaneously fitted with the APEC×PLABS model

lower than the ‘standard’ values ( $\Gamma = 2.10$ , the normalization = 9.7; Toor & Seward 1974).

To simply simulate the effect of  $\Gamma$ , we multiply the APEC model by the PLABS model,  $E^{-\alpha}$ , with  $\alpha = -0.03$  and fit it to the XIS+PIN spectra. The best-fit parameters are obtained to be  $kT = 11.85$  keV,  $Z = 0.30$  solar, and  $K = 1.35 \times 10^{-2}$  ( $\chi^2/\text{dof} = 1343/1219$ ). This indicates that the *Suzaku* temperature measurement has a systematic error at the level of  $\sim 1$  keV, however, the discrepancy between *Suzaku* and *Chandra* becomes even larger in this case. Thus the uncertainty of the *Suzaku* effective area is unlikely to be the major source of the discrepancy.

### 2. *Chandra* ACIS-I

Based on a comparison of cluster temperatures derived from *Chandra* and *XMM-Newton*, Snowden et al. (2008) reported that the *Chandra* temperature tends to be by 1–2 keV higher than that of *XMM-Newton* particularly for the clusters with  $kT \gtrsim 5$  keV. Furthermore, the proceedings of the *Chandra* Calibration Workshop by David et al. <sup>7</sup> indicated the same tendency as well as that the temperature obtained from the fit to the 2–6 keV continuum spectra is systematically higher by about 2 keV than that inferred from the iron line ratios for hot clusters. Thus we consider that the above results suggest that the *Chandra* effective area has a systematic error of the level of  $\Delta kT = +1 \sim +2$  keV for hot ( $kT \gtrsim 5$  keV) clusters. For example, fitting the *Chandra* data with the APEC model multiplied by the  $\alpha = -0.03$  PLABS model leads to  $kT = 12.89$  keV,  $Z = 0.40$  solar, and  $K = 1.44 \times 10^{-2}$  ( $\chi^2/\text{dof} = 569/426$ ). Although the metal abundance is marginally higher, the temperature agrees with that of XIS. Then by simultaneously fitting the *Chandra* and XIS spectra under the APEC×PLABS model and determined  $\alpha$  and the relative normalization factor to be  $-0.017(-0.031 \sim -0.003)$  and  $1.07(1.06 - 1.08)$ , respectively. The best-fit APEC parameters are  $kT = 12.92$  keV,  $Z = 0.35$  solar, and  $K = 1.37 \times 10^{-2}$  ( $\chi^2/\text{dof} = 1890/1636$ ). The result is plotted in Fig. A.1

Based on the above discussion, in order to take into account the difference of the calibration between the two satellites, we assume in §5 the *Chandra* normalization factor relative to XIS of  $1/1.07 = 0.93$  and multiply the spectral model derived with *Chandra* by the PLABS model with  $\alpha = 0.02(0 - 0.03)$ .

<sup>7</sup> [http://cxc.harvard.edu/ccw/proceedings/07\\_proc/presentations/david/](http://cxc.harvard.edu/ccw/proceedings/07_proc/presentations/david/)